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CORONITES FROM THE CHILAS AND JIJAL-PATAN COMPLEXES OF KOHISTAN

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ABSTRACT

This paper describes coronites from the Jijal-Patan and Chilas complexes of northern Pakistan. In Jijal, plagioclase and orthopyroxene reacted under high P–high T metamorphic conditions (~ 850°C, 12–14 kbar) to produce garnet+clinopyroxene coronas. These rocks occur along the MMT suture zone and were metamorphosed at > 40 km depth due to subduction/sinking. In the Chilas complex, orthopyroxene/clinopyroxene/hornblende+spinel coronas developed due to reactions between highly calcic plagioclase and mafic minerals under medium P–high T conditions (750–850°C, 5–7 kbar). These coronas may have formed due to slow cooling, either during uplift or pyroxene granulite facies metamorphism of feldspathic peridotites, troctolites, olivine gabbros, and related rocks. At higher levels during uplift, when the Chilas complex had access to water, labradorite-andesine reacted with mafic minerals to produce thin amphibole and epidote±quartz coronas in noritic granulites. These medium to low P–low T epidote amphibolite facies coronas are mostly very thin but quite common. In rare cases the rocks are more severely affected, thus bridging the gap to epidote amphibolites.

INTRODUCTION

The Chilas complex, up to 40 km in breadth, is a stratiform lopolith stretching west-east for 300 km from Dir to Astor. It consists predominantly of noritic rocks with subordinate ultramafic rocks, troctolites, anorthosites and hypersthene-quartz diorites metamorphosed under pyroxene granulite facies conditions. The complex is emplaced in amphibolites and is intruded on its north by quartz diorites and tonalites. Megascopically identifiable coronas occur in several places in the complex. These coronites range from fieldspathic peridotites to pyroxenites, troctolites, olivine gabbros, and a few norites and anorthosites with highly calcic plagioclase. Olivine coronites were briefly described from Chilas by Shams (1975), Khattak and Parvez (1982), and Bard (1983), and from Swat by Jan (1977), and Jan and Howie (1981a).

Corona development has also taken place locally in the Jijal-Patan area. Here a 200 km^2 wedge-shaped complex comprises a series of ultrabasic-basic rocks that may be magmatically related to the Chilas complex. These rocks have been metamorphosed to garnet granulites at 800–850°C, 12–14 kbar (Jan and Howie, 1981b; Coward *et al.,* 1982; Bard, 1983). The southern 1/3rd of the complex, however, is occupied by a thick slab of alpine-type (ophiolitic) ultramafic rocks devoid of garnet.

In this paper we present an account of the various types of coronas found in the two complexes. Several dozen thin sections of the coronites were studied and hundreds of microprobe analyses have been performed at the universities of Leicester and Peshawar by M.Q. Jan. Details of phase chemistry will be presented in joint papers with B.F. Windley.

CORONAS IN THE CHILAS COMPLEX

Detailed investigations suggest that the coronas in this complex can be grouped into three types: (A) orthopyroxene+clinopyroxene/hornblende+spinel-bearing, (B) amphibole/epidote-bearing, and (C) garnet-bearing. Type A coronas are more conspicuous and well-devleoped, type C the rarest and only microscopically identifiable. Each type is described in some detail in the following:

A) Orthopyroxene+Clinopyroxene/Hornblende+Spinel Coronas.

The best development of these coronas (Pl. 1A) has taken place in feldspathic peridotite and troctolite bodies apparently emplaced in noritic rocks. Such rocks are more abundant around Chilas but isolated bodies occur as far to the west as Madyan in Swat. Small masses of olivine corona gabbros have also been found in the northern amphibolites near Mahodand, Swat Kohistan, in the southern amphibolite belt near Kamila, and 10 km north of Khwaza Khela (cf. Jan and Howie, 1981a). In these localities the coronas are zoned, the zones (i.e. shells) commonly having the disposition olivine → orthopyroxene – hornblende – hornblende+spinel symplectite ← plagioclase. A clinopyroxene shell separates orthopyroxene from hornblende in some rocks.

At Khwaza Khela, the ~ 500m across circular Baba Dherai mound consists of layered ultramafic rocks, anorthosites, troctolites and norites surrounded by the rocks of the southern amphibolite belt. Coronites are common in this mound, the arrangement of shells being olivine → orthopyroxene – clinopyroxene+spinel symplectite ← plagioclase. The Khwaza Khela rock association is very similar to those of Chilas, and it is likely that these rocks and other coronites in the southern amphibolite belt represent intrusions related to the Chilas Complex that have escaped the regional amphibolite facies metamorphism. The close chemical similarity of the olivine-corona gabbro and a neighbouring epidote amphibolite (Table 1) near Kamila clearly suggests that the amphibolite is derived from the coronite.

TABLE 1. CHEMISTRY OF A CORONITE AND NEIGHBOURING EPIDOTE AMPHIBOLITE

	% OXIDES			CIPW NORMS			PPM TRACE ELEMENTS	
	1	2		1	2		1	2
SiO_2	50.08	49.25	Or	0.47	0.42	Ba	< 30	< 30
TiO_2	0.38	0.30	Ab	14.78	13.31	Co	28	37
Al_2O_3	16.44	15.83	An	36.78	35.94	Cr	440	727
Fe_2O_3	1.16	2.18	Cpx	23.08	28.42	Cu	69	63
FeO	5.12	5.36	Hy	13.90	10.54	Ga	17	21
MnO	0.14	0.15	Ol	8.51	7.63	Ni	130	219
MgO	11.53	10.83	Mt	1.68	3.16	Rb	< 10	33
CaO	13.29	14.44	Il	0.72	0.57	Sr	116	158
Na_2O	1.75	1.57	Ap	0.07	0.02	Y	17	17
K_2O	0.08	0.07				Zn	< 30	33
P_2O_5	0.03	0.01				Zr	< 10	15

Analyst : M.Q. Jan

1 is olivine coronite (SI 356A). and 2 epidote amphibolite (SI 355) collected N of Kiru to the south of Kamila. Major oxides in both analyses recalculated to 100% on H_2O-free basis.

The coronas have grown as a result of a reaction between plagioclase and ferromagnesian minerals, notably olivine. The type of participating ferromagnesian mineral and presence of water have controlled the end products in the corona shells. The following succession of minerals has been observed between the ferromagnesian minerals and plagioclase :

i. Cpx → Hbl ← Plg
ii. Cpx → Hbl — Hbl + Sp ← Plg
iii. Opx → Hbl ← Plg
iv. Opx → Hbl — Hbl + Sp ← Plg
v. Ore → Hbl ← Plg
vi. Ol → Hbl + Sp ← Plg
vii. Ol → Opx — Hbl ← Plg
viii. Ol → Opx — Hbl + Sp ← Plg
ix. Ol → Opx — Hbl — Hbl + Sp ← Plg
x. Ol → Cpx ± Sp — Hbl ± Sp ← Plg
xi. Ol → Opx + Sp — Hbl ± Sp ← Plg
xii. Ol → Opx — Cpx — Hbl ← Plg
xiii. Ol → Opx — Cpx — Hbl — Hbl + Sp ← Plg
xiv. Ol → Opx — Cpx + Sp ← Plg
xv. Ol → Opx — Cpx + Sp — Hbl ← Plg

Several dozen optical and microprobe determinations suggest that the coronas have developed in those rocks which contain a highly calcic plagioclase (bytownite or anorthite). The most abundant rocks of the Chilas complex (i.e. norites) in which plagioclase ranges from medium labradorite to andesine are devoid of type A coronas. However, those norites which contain a more calcic plagioclase, and are associated with the peridotite bodies as minor facies, generally are coronitic.

Depending upon the colour index of the rocks, the corona shells may grow around a core of plagioclase (as in feldspathic peridotites) or of a mafic mineral (as in anorthosites). In some ultramafic rocks, patches of hornblende, usually with virmicules or granules of a green spinel and in some cases girdled by orthopyroxene, lie between ferromagnesian minerals. In these the plagioclase must have been small in quantity and grain-size to be totally consumed in the reaction. In bytownite anorthosite-peridotite/pyroxenite layered rocks, reactions between plagioclase and mafic minerals in adjacent layers produced composite secondary layers of corona minerals. Such features have also been reported in some Norweigian coronites (Griffin and Heier, 1973).

The corona minerals in Chilas commonly form shells consisting of polygonal grains that generally do not display a radial growth. However, those near Kamila and to the north of Khwaza Khela, that occur in the amphibolite belt, have complete shells and radiating crystals (Jan and Howie, 1981a). Griffin and Heier (1973) have suggested that Norwegian coronas with fine radiating crystals seem to have formed at lower temperature than those with polygonal grains. In a few rocks the coronas apparently are deformed but, in rare cases, thin amphibole shells completely surrounding pyroxene are in optical continuity.

An unusual coronitic rock was described from the Tora Tigga complex of southwestern Dir (Jan *et al.,* 1983). This rock contains dunitic grapes, reaching over 2 cm in size, in a matrix of hornblende ($\sim 50\%$ modally). The grapes consist of olivine aggregates, hornblende (that cuts the olivine and forms spongy poikiloblasts), and opaque ore. The dunite grapes are separated from the hornblende matrix by thin orthopyroxene shells. A few of the grapes are fractured, the cracks filled by orthopyroxene followed by hornblende.

Microprobe analyses suggest that the green spinel in the coronas is intermediate between spinel proper and hercynite (i.e. pleonaste), and the hornblende is pargasitic (Table 2). An interesting aspect of the phase chemistry of most rocks is that the compositions of pyroxene and hornblende in independent grains, when present, is identical to those in coronas. This may suggest solid state diffusion or metamorphic re-equilibration beyond the limits of coronas sometime after their formation. There also is the possibility that in such rocks all the pyroxene and amphibole has genetic relation with corona development (Asif Khan, pers. comm.).

Pyroxene geothermometry suggests that the Chilas complex, including coronites, have been metamorphosed to pyroxene granulites. Whether the coronites have also passed through the same episodes of deformation as the abundant non-coronitic norites is not clear. Evidence of some deformation is found in the ultramafic rocks which have strained olivine that in rare cases seems granulated with a mortar-like texture. In a few cases, shells in the coronas may be distorted or even broken down (granulated). Thus there is a possibility that despite penetrative deformation, the coronas have somehow remained intact in most rocks. That such may be the case is also suggested by the well-preserved coronas in some rocks of the southern amphibolite belt; this belt has passed through more than two phases of deformation according to Coward *et al.* (1982) and Bard (1983).

TABLE 2. PHASE CHEMISTRY OF TWO CORONITES FROM CHILAS

	G158 Ol	G158 Opx	G158 Cpx	G158 Sp	K60 Plg (4)	K60 Ol (3)	K60 Opx (3)	K60 Cpx (4)	K60 Hbl (5)	K60 Sp (1)
SiO_2	38.67	53.28	51.03	0.13	43.57	39.03	53.27	51.23	44.14	0.94
TiO_2	0.00	0.03	0.00	0.00	0.00	0.00	0.02	0.32	0.66	0.04
Al_2O_3	0.00	3.00	3.61	64.83	35.24	0.10	3.01	3.17	14.07	61.93
Cr_2O_3	0.03	0.00	0.09	0.02	0.06	0.05	0.07	0.23	0.20	0.22
FeO^T	19.15	14.17	6.93	19.05	0.08	19.13	12.31	4.27	7.23	18.28
MnO	0.24	0.33	0.17	0.29	0.03	0.25	0.28	0.16	0.13	0.06
MgO	42.50	28.92	15.60	16.10	0.19	41.30	28.68	15.36	15.65	16.53
CaO	0.00	0.30	22.63	0.27	19.85	0.02	0.47	24.00	12.81	0.23
Na_2O	0.00	0.01	0.27	0.00	0.57	—	0.52	0.45	1.96	—
K_2O	0.00	0.00	0.16	0.00	0.00	0.03	0.00	0.02	0.07	—
NiO	—	—	—	—	0.02	0.06	0.04	0.14	0.09	0.20
TOTAL	100.59	100.04	100.49	100.68	99.61	99.97	98.67	99.35	97.01	98.46
CATIONS PER 4 (OL); 6 (PXN); 23 (HBL); AND 32 (PLG, SP) OXYGENS										
Si	0.986	1.909	1.886	0.026	8.116	1.000	1.922	1.901	6.360	0.197
Al	0.000	0.127	0.157	15.725	7.742	0.003	0.128	0.138	2.391	15.290
Ti	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.009	0.071	0.006
Cr	0.001	0.000	0.003	0.003	0.009	0.001	0.002	0.007	0.023	0.036
Fe_T''	0.408	0.425	0.214	*	0.012	0.410	0.371	0.133	0.871	**
Mn	0.005	0.010	0.005	0.051	0.005	0.006	0.009	0.005	0.016	0.010
Mg	1.614	1.544	0.859	4.936	0.052	1.577	1.542	0.850	3.363	5.159
Ca	0.000	0.011	0.896	—	3.965	0.000	0.018	0.955	1.978	—
Na	0.000	0.001	0.019	0.000	0.272	0.000	0.036	0.033	0.546	—
K	0.000	0.000	0.007	0.000	0.000	0.001	0.000	0.001	0.013	—
Ni	—	—	—	—	0.003	0.001	0.001	0.004	0.010	0.034

Microprobe analyses of K60 by M.Q. Jan, and G158 from J.P. Bard (1983).

G158 : Troctolite, 9 km W of Chilas. Also contains Plg (An_{95}) pale brown-green Hbl, green spinel, biotite, magnetite, and quartz. Ol Fo = 79.6; Opx En = 78.0; Cpx Mg = 43.5%, Fe = 11.1%, Ca = 45.4%.
* Spinel formula contains Fe‴ = 0.232. Fe″ = 3.045, and is pleonaste.

K60 : Feldspathic peridotite with Opx–Cpx–Hbl+Sp coronas, from a boulder 1 km N of Singal, Thak Valley.
Plg An=93.7, zoned from An_{87} core to An_{98} margin, its high An content and reverse zoning are due to outward diffusion of Na to be consumed in Hbl. Ol Fo=79.4; Opx En=80.2; Cpx Mg=43.7%, Fe=7.1%, Ca=49.2%, Amph is ferroan paragasitic Hbl.
** Sp contains Fe‴ = 0.399, Fe″ = 2.802 to give stoichiometric formula and is pleonaste.

B) Amphibole/Epidote Coronas.

These coronas (Pl. 1B) are not conspicuous and generally deciphered under the microscope. Throughout the complex, these have locally formed in norites and related rocks along the contacts of plagioclase (usually labradorite) and pyroxenes or opaque oxide. The amphibole forms thin shells around the mafic minerals and the epidote occurs in discrete shells, girdles of granules, or small patches. The epidote is accompanied by vermicules or tiny granules of quartz, these and/or Fe-oxide may also accompany the amphibole. The following mineral zones have been observed in these coronas :

i. Cpx → Epi+Qz ← Plg
ii. Cpx → Bluish green Amph—Epi+Qz ← Plg
iii. Opx → Bluish green Amph ← Plg
iv. Opx → Colourless Amph—Bluish green Amph ← Plg
v. Fe oxide → Amph ← Plg
vi. Fe oxide → Epi ± Qz ← Plg
vii. Fe oxide → Bluish green Amph—Epi+Qz ← Plg.

The colourless amphibole may be cummingtonite and the bluish green variety appears to be hornblendic. In some rocks, the pyroxene cores are steatised or serpentinized and in a few cases a talc shell separates the pyroxenes from the amphibole shell. It seems that the coronas resulted due to reactions between plagioclase and ferromagnesian minerals under epidote amphibolite- to greenschist facies conditions. The development of talc and serpentine, however, took place at the expense of pyroxene without involving the participation of plagioclase. In a few rocks considerable amount of the pyroxenes has been consumed, thus bridging the gap between epidote amphibolites and type B coronites.

C) Garnet-bearing Coronas.

Garnet coronas (Pl. 1C) were found in one sample collected from the edge of Baba Dherai mound at Khwaza Khela. The rocks here, as mentioned earlier, resemble those of the Chilas area but commonly contain orthopyroxene—clinopyroxene+spinel coronas. The coronite under discussion consists of plagioclase, two pyroxenes, brown hornblende, chromian spinel and pleonaste. Almost all grains of plagioclase and chromian spinel are separated mutually and from those of mafic silicates by a shell of garnet with or without myrmekitically grown opaque oxide. The garnet appears to have grown in response to reactions between aluminous and mafic phases. Its shells are mostly 0.1 to 0.5 mm thick but a few are over a millimeter in thickness.

A brief review of garnet coronas of type C from other parts of the world has been given by Engel and Vogel (1966). They have attributed their formation to reactions occurring during regional metamorphism. The presence of garnet may be suggestive of higher pressure conditions than were operative during the growth of type A and B coronas in the Chilas complex. However, the rarity of the garnet corona and relative abundance of the pyroxene+spinel corona in the Khwaza Khela

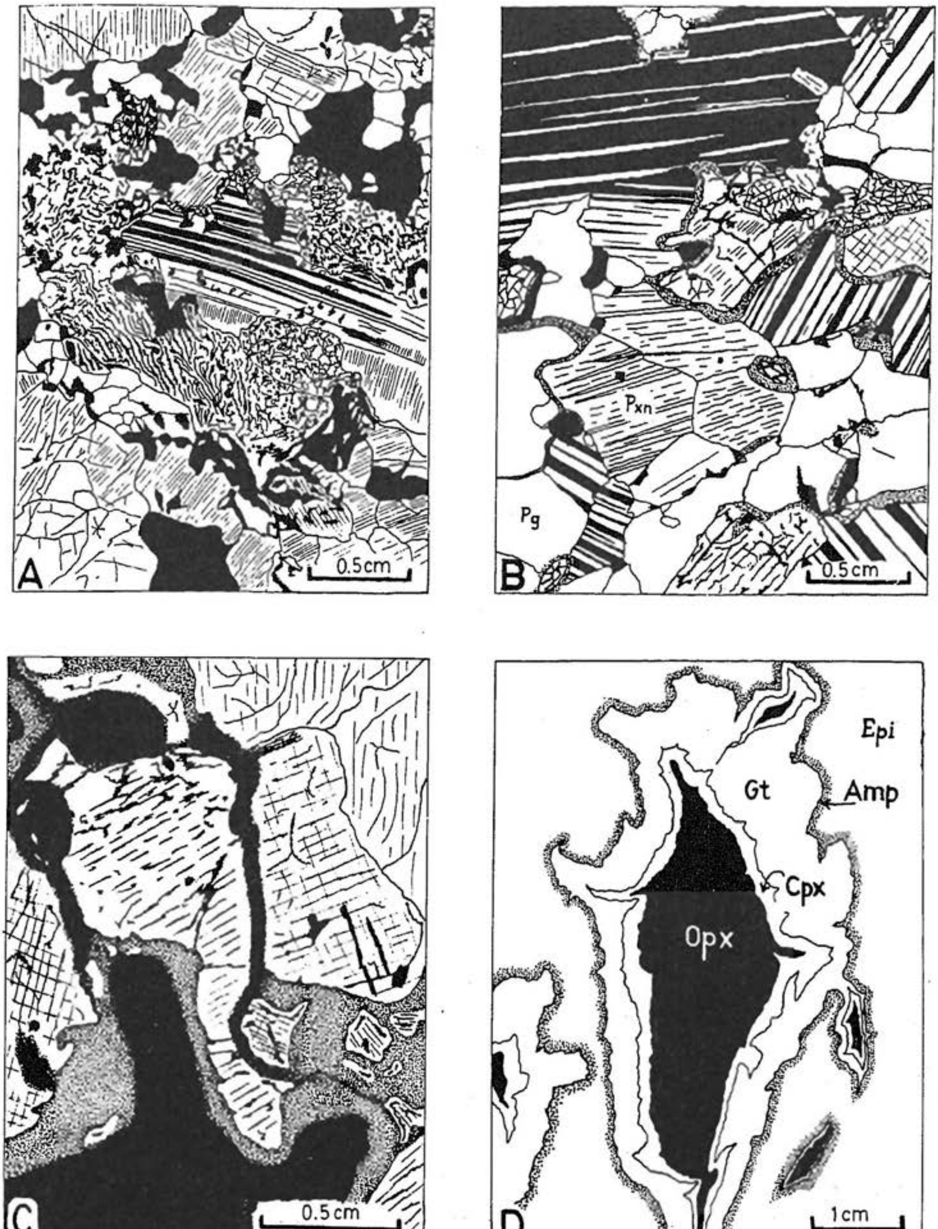

Plate 1. Four types of coronas in mafic granulites from the Chilas and Jijal-Patan complexes of Kohistan. (A) Olivine $\rightarrow$ orthopyroxene $\rightarrow$ clinopyroxene + spinel symplectite $\leftarrow$ plagioclase coronas of the Chilas complex. At the left lower corner is olivine. The symplectite also contains some brown hornblende. Sample 3 km N of Madyan. (B) Thin amphibole and/or epidote coronas (stippled) developed during uplift of the pyroxene granulites of the Chilas complex. (C) Garnet-bearing coronas of the Khwaza Khela area. Stippled area is garnet $\pm$ opaque oxide grown due to a reaction between mafic silicates and aluminous phases (plagioclase and, in figure, chromian spinel). (D) Large coronas of the Jijal-Patan complex near Ziarat, Duber stream. These seem to have developed due to a reaction between orthopyroxene and calcic plagioclase. However, almost all of the plagioclase is now converted to zoisitic epidote.

outcrop are puzzling. Chemical analyses are required to see the influence of bulk composition in this case, and the possibility of a nearby shear zone should not be totally ruled out.

CORONITES IN THE JIJAL–PATAN COMPLEX

The Jijal-Patan complex consists of gabbros, feldspathic peridotites, pyroxenites, and related rocks metamorphosed to high-P garnet granulites at ~ 850°C, 12–14 kbar (Jan and Howie, 1981b; Bard, 1983). Common assemblage in the gabbros consists of garnet+clinopyroxene+plagioclase+quartz+rutile±epidote± hornblende and in the more basis rocks garnet+clinopyroxene±hornblende. Plagioclase does not co-exist with either olivine or orthopyroxene; metamorphic conditions were such that the pairs reacted to form garnet+clinopyroxene. Evidence of plagioclase+orthopyroxene reaction have been found in rare cases where the two minerals are separated from each other by a corona of garnet+clinopyroxene (Pl. 1D).

Metabasites in Lilauni area, southwest of Jijal and to the north of Shangla blueschist, have also suffered a high-P regional metamorphism. In this area of the southern amphibolite belt, garnet is more extensively developed over a wide range of composition compared to elsewhere in the belt, and some rocks resemble mineralogically those of the Jijal Patan complex. In the less affected gabbroic rocks, garnet-bearing coronas with the following zonal arrangement have developed :

i. Opaque oxide → Gar ← Plg
ii. Opaque oxide → Gar ← Cpx
iii. Cpx_1 → Qz — Gar ← Plg
iv. Opx → Qz—Gar ← Plg
v. Opx → Cpx_2—Qz—Gar ← Plg

In the Jijal complex near Ziarat (Duber Stream), a spectacular pegmatoid with coronitic structure occurs. Here, orthopyroxene grains and up to several centimeter long aggregates are encased in coronitic shells reaching over 5mm in thickness. The coronas lie in a matrix of white to locally bluish epidote (zoisite) showing only a slight difference in pistacite content. Several thin sections of this rock have been studied and more than 100 point analyses by microprobe have been performed. The arrangement of minerals from orthopyroxene outwards in the best developed coronas is as following :

Opx → Cpx+Amph — Gar —Amph — Epi

The zones of minerals may differ in other coronas in the same rock. One consists of Amph — Gar — Cpx — cloudy ? Plg. There are simpler arrangements as well as those made more complicated due to a later metamorphic growth of amphibole and epidote. There also are late developed patches containing acicular zoisite+ kyanite blades+paragonite+quartz. Green pleonaste, tremolite and chlorite also occur in the rock. Quite obviously, this particular rock has prints of a complex metamorphic and uplift history.

DISCUSSION

On the basis of physical conditions the coronas in the Jijal-Patan and Chilas complexes can be divided into three categories: 1) High P–high T, $P_s \gg P_{H_2O}$; 2) Medium P–high T, $P_s \gg$ to $\geqslant P_{H_2O}$; and 3) Medium to low P–low T, $P_s = P_{H_2O}$. The first one occurs locally in the Jijal-Patan complex, the latter two in the Chilas complex.

In the Jijal-Patan complex, orthopyroxene and plagioclase could not stably coexist under the prevailing conditions and reacted to produce garnet+clinopyroxene coronas. In most rocks the reaction reached completion and either orthopyroxene (more readily olivine in the Si-poor rocks) or, rarely, plagioclase was totally consumed, depending upon the modal ratio of the two phases. The Jijal assemblages are typical of high-P granulite facies of Green and Ringwood (1967). Garnet-clinopyroxene geothermometry (Ellis and Green, 1979; Saxena, 1979; Ganguly, 1979; Wells, 1979) and other considerations suggest that the Alpurai (Jan, unpublished data) and Jijal-Patan granulites were metamorphosed at about 850°C and 12–14 kbar (cf. Jan and Howie, 1981b; Bard, 1983). These rocks occur in the north of MMT (suture zone) and their high-P metamorphism may be due to subduction/burial to depth of > 40 km along the suture zone. During uplift the rocks had access to water and a number of lower grade minerals, especially hornblende, epidote and paragonite, developed.

The medium P–high T coronas in the Chilas complex apparently developed under such conditions that highly calcic plagioclase (bytownite-anorthite) could no more coexist stably with mafic minerals. The plagioclase reacted with olivine to produce orthopyroxene-clinopyroxene/hornblende+spinel coronas, with orthopyroxene to give clinopyroxene/hornblende+spinel coronas, and with clinopyroxene to form hornblende±spinel coronas. Such coronas have been attributed to diffusion during slow cooling after the solidification of rocks or to metamorphism (Mason, 1969; Sapountzis, 1975). Magmatic processes, such as the one proposed by Rai (1979) for Kargil coronites, cannot be applied to the Chilas rocks. In addition to some evidence we have found for diffusion, it will be difficult to produce the observed variety in the mineral parageneses of the Chilas rocks by a late magmatic process. The formation of amphibole or clinopyroxene in different coronas may be a function of variation in the water vapour pressure.

Griffin and Heier (1973) suggested that clinopyroxene+spinel coronas form either due to lowering of temperature (during uplift) from initially higher magmatic temperatures, or to an increase of pressure. Increase in pressure may be brought about by shearing, subduction or sinking under a growing pile of rocks. Various methods of geothermometry (Perchuk, 1969; Wood and Banno, 1973; Obata, 1976; Wells, 1979; Dahl, 1980) suggest that the Chilas coronites finally equilibrated under pyroxene granulite facies at 750–850°C. (These estimates are based on the assumption that equilibrium was maintained during the growth of the coronas. For details of symplectite-forming reactions, see Mongkol and

Ashworth, 1983). The instability of very calcic plagioclase with orthopyroxene or olivine to yield two pyroxenes+spinel, and the absence of garnet suggest that the operating pressure was below 7 kbar at these temperatures (Kushiro and Yoder, 1966; Green and Ringwood, 1967; Obata, 1976). However, the pressure was not high enough to promote such a reaction between a more sodic plagioclase (medium labradorite to andesine) and orthopyroxene in the more abundant norites of the Chilas complex. Bard (1983) suggested that the Chilas coronites formed under pyroxene granulite facies conditions and our data do not contradict him, although the possibility of their development during uplift cannot be ruled out.

The moderate to low P-low T coronas producing amphibole and epidote at the cost of pyroxene and plagioclase are clearly the result of retrograde processes. In the presence of water along the plagioclase-pyroxene interface, they were produced during the uplift of the pyroxene granulites to higher levels and are suggestive of epidote amphibolite facies conditions. The reaction calcic plagioclase+ pyroxene = amphibole+epidote+quartz±less calcic plagioclase has affected a few rocks more extensively than the grain boundaries, thus bridging the gap to epidote amphibolites.

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